

Trapped Particle Effects: Results, Implications, Open Questions

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Two years ago, “trapped particle asymmetry” modes were reported to occur when an applied “squeeze” voltage causes some particles to be trapped axially, and a simple theory explained the observed mode frequencies. Now, it appears likely that trapped-particle-mediated (TPM) effects are dominant in plasma lifetime scalings, transport from applied asymmetries, diocotron mode damping, and possibly even internal viscosity. This talk will attempt to give an overview of what is known [1], where more experiments are needed, and where the theory is lacking.

Electric or magnetic trapping probably occurs in all “long” apparatuses: unintended wall potential variations of 0.1 Volts are common, and it is sobering to note that $\delta_B/B = 10^{-3}$ will trap 3% of the particles. Initial experiments (and all theory to date) considered electric trapping; but magnetic trapping is probably more common and important.

Early experiments focused on the new trapped particle modes, but the important effect is particles scattering across the trapping separatrix. This breaks the v_z adiabatic invariant, allowing 2D potential energy to flow to 3D kinetics, and enabling external asymmetries to generate strong transport. The effect is dominant in low-collisionality plasmas because the separatrix dissipation scales with collisionality as $\nu^{1/2}$, whereas most other effects scale as ν^1 . Here, the collisionality can be electron-electron, electron-neutral, or externally stimulated. The effect can be also be described as dissipation of asymmetry-induced equilibrium currents, as in the original theory analysis for bootstrap current in Tokamaks.

Thus, it now appears likely that most of the $(L/B)^{-2}$ lifetime scalings from “background asymmetries” can be given interpretation in terms of the (partially) known scalings for TPM transport. The measurements of transport from *applied* electric and magnetic asymmetries (Fine, Kriesel, Eggleston, Gilson) also should be compared to TPM predictions. “Anomalous” damping of diocotron modes (Fine, Sarid, Paul) is almost certainly related to TPM effects. TPM transport also has important implications for containment of large numbers of positrons or pBars, since the TPM loss rate generally scales as total charge Q^2 , *independent of length*.

Theory provides a reasonable picture of trapped-particle-mode damping with electric trapping, but modes in the magnetic trapping case remain enigmatic. Theory can not yet explain the observed particle transport scalings for either case, but this appears imminent for electric trapping. Diocotron mode damping has not been worked out theoretically. Finally, it is possible that TPM effects are important for seemingly unrelated effects such as viscosity. Here, the theory predictions rely on exact reversals of drift kinetics; but these reversals could easily be upset by TPM effects.

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Thermal Fluctuations: Modes versus the Continuum

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Two procedures have been described for determining the temperature of pure electron plasmas at or near thermal equilibrium by measuring the spectrum of the fluctuating charge on a sector probe. The first [1] method employs the narrow resonant peaks associated with the modes of the plasma, and the second [2] makes use of the broad continuous spectrum associated with the independent particle motion. A simple model of the plasma column, based on the fluctuation-dissipation theorem and using the warm plasma dielectric function, yields a fluctuation spectrum with both features. Modes whose axial phase velocity are more than 3-4 times the electron thermal speed are lightly damped and are clearly separated from the continuum. If the axial phase velocity of a mode becomes less than 1-2 times the electron thermal speed, then the mode becomes strongly Landau-damped and it merges into the continuum. Since mode velocities are of the order of $\omega_p a$, where a is the plasma radius, the plasma radius must be at least several deBye lengths in order to have lightly damped modes. In general, the spectrum is a mixture of a continuous spectrum together with a finite number of modes which are Landau-damped by varying amounts, depending on their phase velocity relative to the electron thermal speed. Only in the extreme limit, $\omega_p a \ll v_{th}$ does the continuous spectrum tend to a Gaussian of width $k v_{th}$, characteristic of independent particles.

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Large Amplitude Trivelpiece-Gould and BGK Modes in Pure-Electron Plasma Columns¹
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We observe both Trivelpiece-Gould (TG) and BGK modes in the Berkeley electron trap. The TG modes occur at low plasma temperatures, and are characterized by a set of distinct linear frequencies. As the amplitude of the TG modes increase, their oscillation frequency increases by approximately 10%. At low amplitudes, the TG modes are pure, and the harmonic content of the TG modes reversibly increases with amplitude. The TG mode Qs are near 600.

BGK modes occur at high plasma temperatures; the temperature range in which both BGK and TG modes occur is limited. The BGK modes exhibit no distinct linear frequencies, and can be excited over a frequency range of more than a factor of three. As the amplitude of the BGK modes increase, their frequencies *decrease* by as much as a factor of two. However, there is no one-to-one correspondence between the mode amplitude and frequency. The BGK modes have an extended harmonic structure that persists even as the modes decay to low amplitude. Typical BGK modes Qs are near 5000, but sufficiently high temperature plasmas can have Qs greater than 25000. Experiments suggest that BGK mode damping is due to collisions.

Experiments demonstrate that, as expected, the BGK modes depend on specific classes of trapped particles. Tailoring the distribution function and the number of trapped particles affects the mode amplitude. Oscillation in the trapping potential can be observed.

Our experiments build on work by Moody and Driscoll, Hart and Peterson, and Yamazawa and Michishitain in which TG modes and solitons were observed. Most of the previous experiments were done by effecting catastrophic changes to the target plasma, or by applying fixed frequency, large amplitude drives. Here we employ low amplitude autoresonant (swept frequency) drives and plasma temperature variations to explore new phenomena.

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Case-van Kampen Approach to Cold Fluid and Warm Fluid Plasma Oscillations

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The plasma oscillations of a confined plasma are examined both analytically and numerically using both cold fluid and warm fluid theory. In cold fluid theory, a plasma with uniform density and a sharp boundary has well-defined discrete normal modes. These modes can be determined analytically for spheroidal plasmas, and for more general plasma shapes they have also been considered numerically by several authors [1].

However, we show that when the edge of the plasma is not sharp, the discrete eigenmodes of the potential become quasimodes due to spatial Landau damping. These quasimodes are nothing more than the famous Tonks-Dattner resonances. A Case-van Kampen analysis of the cold fluid theory shows that the damped quasimodes can be described as a superposition of a continuous spectrum of Case-van Kampen eigenmodes with real frequencies.

These Case-van Kampen modes form a complete set with respect to an inner product involving the plasma density as the weight function, and they can be obtained numerically rather easily using methods similar to those used previously for diocotron modes. Examples of this approach are provided for both unmagnetized plasma oscillations in a spherical neutral plasma, of interest to experiments in ultracold neutral plasmas, and magnetized plasma oscillations in nonneutral plasmas of various shapes.

The effect of warm-fluid corrections on the frequency of the low-order modes has been considered as a possible temperature diagnostic in nonneutral plasmas. Surprisingly, when warm fluid corrections are added to the theory in a slab geometry plasma with a thermal equilibrium profile (the limit of a highly-oblate plasma pancake), the continuous spectrum of cold fluid theory returns to a discrete spectrum of undamped normal modes. Thermal corrections to the modes frequencies can then be easily obtained numerically. Thermal corrections will also be discussed for more general plasma shapes.

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Continuous Injection into Electron Plasma Traps

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Computational studies and experimental measurements of plasma injection into a Malmberg-Penning trap reveal that the number of trapped particles can be an order of magnitude higher than predicted by a simple estimates. The increase in trapping is associated with a rich nonlinear dynamics generated by the space-charge forces of the evolving electron density. A particle-in-cell simulation is used to compare with experimental and to identify the physical mechanisms that lead to the increase in trapped electrons. The simulations show strong two-stream interactions between the electrons emitted from the cathode and those reflected off the end plug of the trap. This is followed by virtual cathode-like oscillations near the injection region. During this process the initially hollow longitudinal phase-space is filled, and the transverse radial density profile evolves so that the plasma potential matches that of the cathode. Simple theoretical descriptions of the different dynamical regimes are presented and good agreement is found between simulation and theory.

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Using Variable Frequency Asymmetries to Understand Radial Transport in a Malmberg-Penning Trap¹ D.L. EGGLESTON, Occidental College — It has long been known that asymmetric electric and magnetic fields produce radial transport in Malmberg-Penning traps, and much work has been done to understand this transport. Our approach is to apply a variable frequency electric asymmetry to a low density population of electrons and to measure the resulting radial particle flux Γ as a function of radius r . The low particle density eliminates many plasma modes (which have their own frequency dependence) and allows us to focus on the transport physics. The usual azimuthal $E \times B$ drift is maintained by a biased central wire, and this arrangement also allows us to independently vary the drift frequency ω_R by adjusting either the axial magnetic field B or the bias of the central wire ϕ_{cw} . Up to forty wall sectors are used in order to apply an asymmetry consisting of a single fourier mode (n, l, ω) , where n is the axial wavenumber, l is the azimuthal wavenumber, and ω is the asymmetry frequency. In the current experiments, we vary ω , n , ϕ_{cw} , and B . As ω is varied, the particle flux shows a resonance similar to that predicted by resonant particle theory². The peak frequency of this resonance f_{peak} increases with ω_R and varies with n , in qualitative agreement with theory, but when quantitative comparisons are made the experimental values for f_{peak} do not match those predicted by theory. Instead, the dependence of f_{peak} on ϕ_{cw} , B , and r follows simple empirical scaling laws: for inward directed flux, $f_{peak}(\text{MHz}) \approx [-R\phi_{cw}(\text{V})/rB(\text{G})]^{1/2}$, where R is the wall radius, and for outward directed flux, $f_{peak}(\text{MHz}) \approx 0.8[-\phi_{cw}(\text{V})/B(\text{G})]^{1/2}$. These results³ may provide guidance for the construction of the correct theory of asymmetry-induced transport.

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Prefer Oral Session
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Shear-Limited Test Particle Transport in 2D Plasmas

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Measurements of test-particle transport in pure ion plasmas show 2D enhancement over the 3D diffusion rates, limited by the shear in the overall $\mathbf{E} \times \mathbf{B}$ drift rotation $\omega_E(r)$. For finite plasma length L_p , axially bouncing particles may undergo many correlated collisions before rotational shear separates them in θ . This number of bounces $N_b \equiv (\bar{v}/2L_p)/(r\partial\omega_E/\partial r)$ characterizes the approach to the 2D “bounce-averaged” regime.

In the 3D regime of $N_b \lesssim 1$, the measured diffusion agrees quantitatively with recent theories of long-range $\mathbf{E} \times \mathbf{B}$ drift collisions, and is substantially larger than predicted for classical velocity-scattering collisions. For shorter plasmas with $1 < N_b < 100$, the measured diffusion is enhanced by a factor roughly proportional to N_b [1]. For short plasmas with exceedingly small shear ($N_b > 1000$), we observe transport rates consistent with estimates for shear-free 2D plasmas dominated by thermally-excited “Dawson-Okuda” vortices.

This N_b -enhancement over the 3D diffusion rates may also be viewed as a shear-reduction of 2D diffusion rates. From this perspective, recent theory has provided a rigorous calculation of transport in a 2D point-vortex gas with shear [1]; and the measurements are in qualitative agreement with the theory.

Most interestingly, recent measurements in the low shear regime show *non-diffusive* transport, as would be expected from convection in large thermal eddies. Here, the measurements are severely limited by rotational averaging during the data collection time. A proposed stroboscopic laser imaging technique could provide direct imaging of thermal eddies in the presence of controlled shear, providing direct quantitative tests of shear-limited eddy diffusion.

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Experiments with Fluid Echoes in a Non-Neutral Plasma

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We have observed a nonlinear fluid echo in magnetized electron columns, demonstrating the reversible nature of spatial Landau damping. Two diocotron waves with initial and second azimuthal mode numbers m_i and m_s are excited separated in time, and a third diocotron wave with mode number $m_e = m_s - m_i$ appears as the echo. These waves also represent Kelvin waves on a rotating ideal fluid. The wave damping, or phase mixing, can be seen in experimental images [1] as the spiral wind-up of the density perturbation, and the unwinding results in the echo.

Experiments agree with theory [2] on the mode number and appearance time of the echo. We have observed echoes using mode numbers 2 - 6; however, no center-of-mass $m = 1$ echo is seen, and no echo is seen using $m = 1$ as the initial or second waves, presumably due to the unique wall-location of the $m = 1$ critical radius. Moreover, the echo shows a nonlinear “saturation” with the second wave amplitude, in quantitative agreement with a simple ballistic theory [3].

Surprisingly, the echo is not destroyed by v_z -dependent particle drifts in the end confinement fields [4]; in essence, separate v_z -classes of particles execute separate wind-up and unwinding, resulting in the same echo. At late times, the echo is destroyed due to weak collisional velocity scattering between these separate v_z -classes. In addition, very large second wave excitation is observed to corrupt the initial wave’s density filament pattern, suppressing echo formation; but this effect is not yet understood.

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